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14. ABSTRACT

The Final Proceedings for Fourth Symposium on Global Flow Instability and Control, 28 September 2009 - 2 October 2009
The fourth in the series of symposia established in 2001 was held in Hersonissos, Crete, Greece, having as its primary objective the creation of a forum for presentation and discussion of current research and open issues in global flow instability and control. This has been particularly interesting in recent years (especially since the last symposium, held in 2005), in view of the increasing adoption by the community of instability analysis and theoretical flow control approaches based on the pertinent two- and three-dimensional partial-derivative eigenvalue problems.
Focus was again placed on advances in theory, numerical algorithms, and experiment, which enable identification and control of fluid flow global instabilities in real-world applications. Highlights of this year's edition of the symposium have included discussion of enabling technologies for complex flow instability analysis and control, as well as the connection of results of the new theory to known (from a physical point of view) applications to weakly-nonparallel flows. In addition, nonlinear global instability analyses were presented, as were novel flow control (theoretical) ideas and practical implementations. As planned by the Organizing Committee, topics discussed included: 1) Global instability and control of flows, the basic state of which is inhomogeneous in two or all three spatial directions; 2) Experimental and computational investigations and demonstrations of open and closed-loop control; 3) Theoretical, computational, and experimental work on transient growth in such flows, and in particular the relation of transient growth to flow control; 4) Flow control methodologies, including optimal control, adjoint-based methods, and reduced-order modeling; and 5) Accurate and efficient algorithms for the numerical solution of large (partial-derivative) eigenvalue problems and direct numerical simulation.

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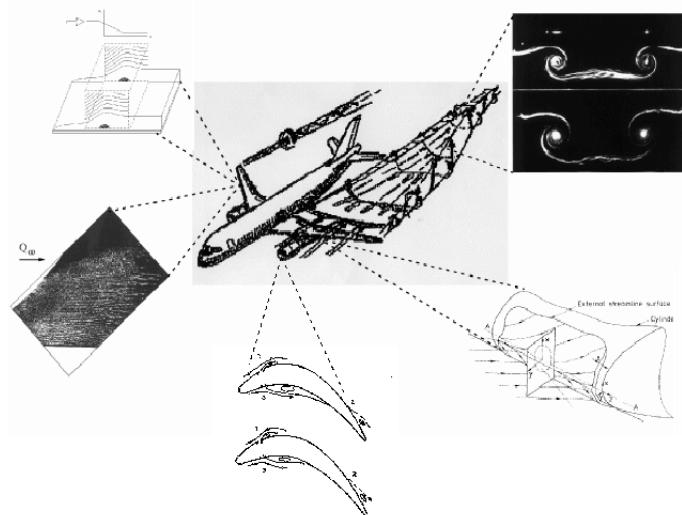
A synthesis of presentations and discussions

written by
V. Theofilis

based on notes provided by:
L. González, D. Greenblatt, M. Karp, D. Rodríguez, P. J. Schmid and A. Tumin

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1. Introduction

The fourth in the series of symposia established in 2001 was held in Hersonissos, Crete, Greece, September 28 – October 2, 2009, having as its primary objective the creation of a forum for presentation and discussion of current research and open issues in global flow instability and control. This has been particularly interesting in recent years (especially since the last symposium, held in 2005), in view of the increasing adoption by the community of instability analysis and theoretical flow control approaches based on the pertinent two- and three-dimensional partial-derivative eigenvalue problems.

Once again, the audience encompassed specialists, who have contributed to pioneering developments in these fields and are willing to promote the synergy between theory, experiment and computation in order to advance both the frontiers of knowledge and technology transitions. As a testimony to the interest in this area of research, editors of the ten major fluid mechanics journals were amongst the audience, presenting ongoing research results and contributing substantially to the discussion groups. On the other hand, the largest percentage of young researchers to have ever attended a Crete meeting was present during this edition, an encouraging sign

Focus was again placed on advances in theory, numerical algorithms, and experiment, which enable identification and control of fluid flow global instabilities in real-world applications. Highlights of this year's edition of the symposium have included discussion of enabling technologies for complex flow instability analysis and control, as well as the connection of results of the new theory to known (from a physical point of view) applications to weakly-nonparallel flows. In addition, nonlinear global instability analyses were presented, as were novel flow control (theoretical) ideas and practical implementations. As planned by the Organizing Committee, topics discussed included:

- Global instability and control of flows, the basic state of which is inhomogeneous in two or all three spatial directions
- Experimental and computational investigations and demonstrations of open and closed-loop control
- Theoretical, computational, and experimental work on transient growth in such flows, and in particular the relation of transient growth to flow control
- Flow control methodologies, including optimal control, adjoint-based methods, and reduced-order modeling
- Accurate and efficient algorithms for the numerical solution of large (partial-derivative) eigenvalue problems and direct numerical simulation

Two thematic sessions were organized during the Symposium, based on the above topics. Each session was introduced by a keynote address and was followed by short contributed presentations, each of which was be granted long discussion time. Split-out groups were formed after these presentations, which discussed the respective session topic. In this manner the two main targets of the symposium were met: to reach a consensus on past achievements and to identify future research avenues.

2. Presentations

2.1 Session I: Theoretical Foundations (Day 1)
(Session chaired by P. J. Schmid. Notes by P. J. Schmid; edited by V. Theofilis)

John Kim, presented an invited talk on the *"Physics and control of turbulent boundary layers"*, movitated by the need to test controllers under realistic conditions in true simulations of turbulent boundary layers and to assess their performance limits, measured by the amount of drag reduction that can be accomplished. He showed that a necessary prerequesite for that is a sound understanding of the underlying physical mechanisms of skin-friction drag and expertise in utilizing tools from modern control theory. Two questions arise in this context: (i) what is the flow physics behind skin-friction drag in turbulent boundary layers? and (ii) what levels of drag reduction can be expected? Answers to the first question involve the presence of streamwise vortices which appear in tandem with high turbulent boundary layer drag, such that control of streamwise vortices reduces drag. Streamwise vortices play an important role via the self-sustaining process (Hamilton, Kim, Waleffe 1995) via the self-sustaining near-wall turbulence (triad) mechanism proposed by these authors:

Streamwise Vortices

nonlinear

linear

linear

**Streamwise-varying Flow**

Streamwise Streaks
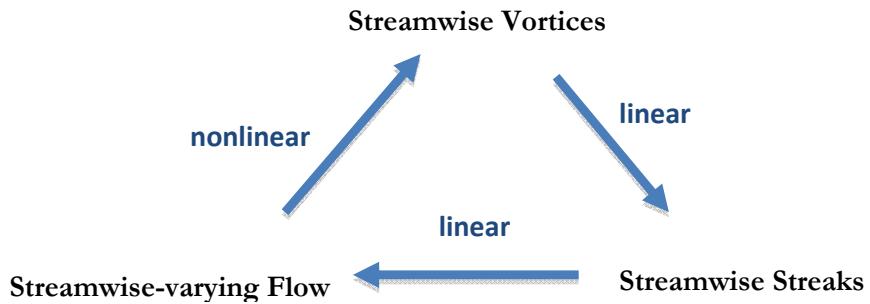
Figure 1. The triad mechanism of self-sustaining near-wall turbulence (Hamilton, Kim, Waleffe 1995)

The linearity of two out of three elements of this cycle permits use of linear flow control; a key theoretical result is that absence of streamwise vortices (by LQH control, use of hydrophobic surfaces, or addition of polymers) yields significantly reduced skin-friction drag. Incorporating a controller into a non-normal system and using a special form of the control gain for opposition control, it is possible to achieve significant drag reduction by breaking the self-sustaining process at the stage where streamwise vortices are transformed into streaks. Even though this type of simulations is "virtual", valuable information can be gained about drag-producing mechanisms and their control by wall blowing and suction. The second question, about the lowest achievable level of drag, has been investigated by introducing an upstream propagating blowing/suction wave in a turbulent channel flow which produced drag value below the laminar one, thus updating an earlier conjecture of Bewley. The underlying mechanism relies on a clearing of streaky structures in the near-wall region. A net-performance analysis, taking into account the power expended and the power saved, resulted in a modification of Bewley's conjecture that still suggests the relaminarization of the flow as the best control strategy. The main conclusions have been that (i) key elements in the self-sustaining mechanism are linear, and as such can be analyzed from a linear-system operator perspective and (ii) traveling wave control can lead to lower-than-average drag.

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Hall and Sherwin in two related talks presented a combined asymptotic and numerical study of *"Streamwise vortices in shear flows",* and the interactions thereof with waves in the same class of flows. Starting point has been the vortex-wave interaction theory proposed by Hall & Smith in 1988, in which longitudinal vortices are driven by and in turn interact with the critical or wall layer of the shear flow. The wave/vortex theory can be related to more recent concepts such as "exact coherent structures" (Waleffe 1995, 1999), "edge-states" (Hof, Eckhardt 2004) or "coherent structures" (Kerswell). The central equations consist of a pressure wave equation, i.e. the two-dimensional version of the familiar Rayleigh-equation proposed by Hall & Horseman (1990), which is coupled to a streak/roll equation in which the pressure enters in form of jump conditions across the critical layer. The combined system represents a nonlinear eigenvalue problem, in which the key mathematical challenges have been (i) the spatially-varing nature of the critical layer and (ii) the absence of coupling between the (essentially nonlinear, due to the critical layer) two-dimensional Rayleigh equation and the ensuing streaky flow. The numerical solution of the governing equation has been accomplished using a spectral/hp element method where jump conditions, dictated by the asymptotic analysis, have been incorporated by modified delta-function forcing terms. A system of equations has been derived based on the identified Reynolds number scaling from the previous asymptotic study. Using streaks as a mean flow for a time-stepper Arnoldi approach based on a pseudo-Reynolds number, a good match between the asymptotic scalings and the numerical results has been found.

Okino & **Nagata** introduced a *"Nonlinear solution of flow in a square duct"*, motivated by the (global linear analysis) result of Tatsumi & Yoshimura (1990) that flow in a square duct or, more generally, flow in rectangular ducts with cross-sectional aspect ratios less than 3.2 is linearly stable. As a consequence, the absence of linear criticality makes it impossible to use weakly nonlinear expansions or center manifold theory to arrive at exact coherent structures. Rather, a homotopy method has to be employed to follow solutions to the nonlinear governing equations in parameter space. As a starting point for the homotopy method the Boussinesq approximation for thermal flow in a square duct with internal heat sources is used. For a constant Prandtl number of Pr=7, the remaining parameters (the Reynolds and Grashof number) are varied, and an unstable wedge in the Re-Gr-plane arises where the mean flow becomes inflectional. A two-dimensional Chebyshev-based global stability analysis using a nonlinear Galerkin approach and taking advantage of symmetries revealed oscillatory behavior associated with a streamwise vortex and a low-speed streak once the solution is followed to the isothermal (Gr=0)-solution.

Meliga & **Chomaz** discussed *"Global stability and adjoint-based control of a confined impinging jet".* The starting point of their contribution has been the customary classification of fluid systems into oscillators and amplifiers, according to their response to a localized impulsive forcing. From a global point of view, oscillators are associated with unstable global modes, whereas amplifiers contain non-normal global modes. Nonnormality in a system furthermore has to be distinguished between lift-up (or componentwise or shear-based) non-normality and convective nonnormality (stemming from the mean shear terms). These concepts have been applied to a jet impinging on a flat wall which models processes involved in the cooling of steel sheets emerging from a galvanization bath. The problem is tackled numerically using a finite-element discretization, sparse multifrontal solvers and the implicitly restarted Arnoldi method. Performing the direct/adjoint analysis introduced by Luchini & Giannetti (Crete II – 2003), they found that the mean flow contains a recirculation region which is the focus of an adjoint global mode analysis, a result which confirms that a wavemaker exists inside the first recirculation bubble. This result is in line with analogous experience in the wake of a circular cylinder (Hill AIAA 1992) and a recirculation bubble on a flat-plate (Rodríguez & Theofilis JFM 2010). The same location is also identified as most sensitive to mean flow changes, a first indication for a possible application of passive control devices such as small cylinders, as successfully demonstrated by Strykowski & Sreenivasan in the wake of the cylinder.

Garbaruk, Magidov & **Crouch**, in their presentation "*Quasi-3D analysis of global instabilities: vortex shedding on a wavy cylinder*" introduced renewed efforts on global instability analysis of realistic-shaped wings, extending their earlier work on the onset of shock buffeting on a NACA 0012 airfoil under transonic conditions. The successful analysis of the latter buffeting problem as a global stability problem and the recovery of a 3-degree critical angle-of-attack for a Mach number of Ma = 0.76 suggested employing an analogous global treatment of the three-dimensional stability of flow around a model wing consisting of a circular cylinder with oscillatory spanwise variations in the diameter. The three-dimensionality of the flow is located where the cylinder diameter is maximal, which is confirmed by the experiments of Chetan & Gaster and which points at subtle but important three-dimensional effects of the baseflow on the overall global stability. Larger diameter variations lead to more localized and more unstable areas of instability. In comparison with the earlier two-dimensional airfoil analysis, taper has been observed to have a net stabilizing effect on the flow.
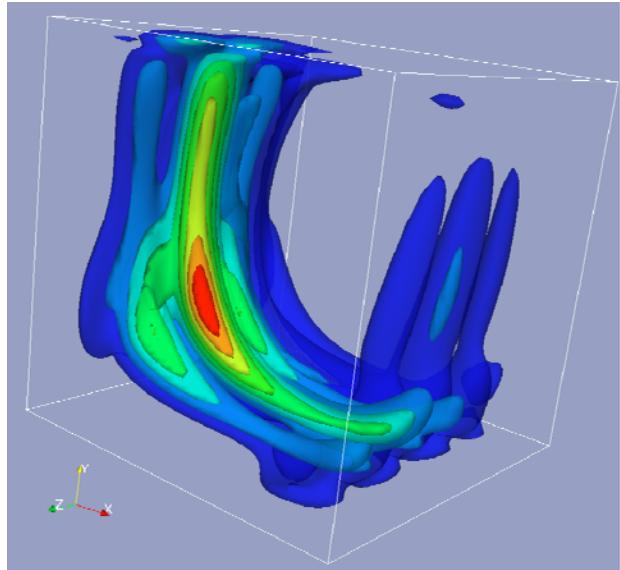

Figure 2. Visualization of a TriGlobal eigenmode component: the streamwise disturbance velocity in the cubic lid-driven cavity at Re=2000 (Luchini, Giannetti, Pralits 2009)

Luchini, Giannetti & Pralits elaborated on "*Sparse-matrix algorithms for global eigenvalue problems*". The main issue identified as a performance bottleneck in standard techniques for global stability problems is the inclusion of convergence acceleration techniques that involve the inversion of large-scale matrices by iterative techniques. This inversion being rather costly, the talk focused on discussing alternative strategies to avoid it; an algorithm was proposed, closely related to an explicit Euler step, based on direct iteration including a shift, the latter chosen so as not to be too close to the desired eigenvalue. Furthermore, application of approximate inversion was suggested for the Arnoldi iteration. The combined algorithm was embedded into a multigrid technique to further accelerate the convergence of the method and to add robustness. Application of the proposed iterative algorithm to analyze instability of three-dimensional cavity flow produced, for the first time, (highly-resolved) three-dimensional global eigenfunctions, one of which is shown in Figure 2.

2.2 Session II: Lifting surfaces – Analysis and Experimentation (Day 1)
(Session chaired by P. Monkewitz. Notes by V. Theofilis)

Hermann Fasel presented an invited talk on *"Reynolds number effects of separation control for lifting surfaces: simulations, laboratory and free-flight experiments",* based on a synergetic approach comprising simulation, laboratory experiments and flight tests. He argued that unexplored alpha and beta flight regimes exist and argued for flight testing of new technologies, eg. active and passive flow control. For the concrete example of interaction of transition and separation he showed CFD of an entire airfoil, in conjunction with DNS in parts of the foil, wind- and water tunnel experiments, as well as flight testing involving the combined efforts of the University of Arizona, Queen Mary College, London and Edwards AFB. He argued the significance of Froude scaling and demonstrated equal Froude numbers for model motor glider and full-scale configuration. The DNS was performed at Re=130,000 on a massive 1 billion gridpoints; for Reynolds number beyond this (record-suspect) Re, hybrid methods based on LES and DES must be used. All research tools utilized were shown to overlap by design. Active Flow Control was performed on a model configuration at Re = 64k, on which plasma actuator prevents massive separation (and stall). He went on to discuss the physics of long- and short separation bubbles, alongside a new classification of both the bubbles themselves, as well as their bursting. Laboratory experiments performed in a water tunnel at U of A delivered shedding frequency. Subsequent POD analysis showed that the two-dimensional instability is the most energetic. Excellent comparison with linear stability theory was shown, leading to the conclusion that the phenomena studied involve convective and not global instability. He went on to explore anomalous lift-curve behavior with 2-D and 3-D DNS and was able to pinpoint the differences in the unphysical 2-D DNS predictions. At higher AoA the leading edge bubble was examined and it was claimed that its instability is not the result of a convective/shear-layer mode. The same conclusion was arrived at by analyzing spectra and three-dimensionality. Although in earlier presentations he suspected a global mode, in the present discussion no attributes were given to this instability. Finally, the effect of free-stream turbulence, modeled by random forcing, was studied and it was shown that FST develops into Klebanoff modes. He attributed the differences between long- and short bubbles to minute amounts of FST: even 0.4% was sufficient to close an otherwise (wide) open bubble.

Stalnov, Fono and **Seifert** discussed *"Closed-Loop Bluff-Body Wake Stabilization via Fluidic Excitation"* and showed PIV results in the wake of a circular cylinder at Re=250, with the objective of using opposition control to delay global instability in the wake. They first described the Tel-Aviv University piezo-fluidic actuators and PIV setup, alongside the body-mounted sensors. They went on to describe a closed-loop Active Flow Control (AFC) diagram, including a phase-locked loop (PLL) flow control strategy. The latter was shown to be able to extract a signal with a known frequency and phase, while the AFC strategy is to control the phase. The approach followed first collapsed the vortex-shedding frequency and then used a phase detector in order to control phase as the single free parameter of the problem. Reduction of the fluctuations in the entire wake was demonstrated. The main thesis of this part of the work has been that in order to stabilize the flow, data in addition to those delivered by wake-sensing must be available and utilized. Using a single surface-mounted sensor, PIV results demonstrated that the bubble can be elongated. Future work will include an attempt to stabilize turbulent flow, which is expected to be feasible so long as the flow is dominated by vortex shedding alone.

González, Artana, Gronski and D'Adamo, in their talk entitled *"An electrodynamic analogy of the moving surface control mechanism in bluff bodies",* presented Active Flow Control (AFC) work motivated by the need to reduce vibrations, improve mixing and optimize lift/drag in the wake of bluff bodies. AFC mechanisms which have been used in this context have been: uniform / non-uniform, stationary rotation/ non-

stationary rotation, mass injection and Electro-hydrodynamic (EHD) actuators. The talk was focused on the last approach, whereby a "computational analogy" of EHD was introduced, in the sense of devising appropriate boundary conditions in order to mimic complex local electric-field-induced volumetric force. They provided justification for their approach on the grounds of the strong but local (due to plasmas) density and viscosity changes and alluded to the difficulties of meshing moving parts in terms of both memory and small time-steps. The approach taken substituted the physical AFC mechanism by "electroconvection", which was explained as movement of ionic particles, leading to linear momentum transfer, in turn giving rise to tangential ionic fluid. The injection parameter used as a control mechanism was analogous to a revolving small-radius cylinder replacing the sharp trailing edge of the bluff body. Global instability analysis of the configuration was performed, in which the steady basic state solution is obtained by two-dimensional DNS on 130k Taylor-Hood finite-element nodes, and 1.2e7 non-zero matrix elements. Validation results were presented on the circular cylinder, and two novel rounded backside configurations, were analyzed, one (I), analytically- and the second, (II), numerically-constructed. Critical Reynolds numbers were obtained at 175 and 190, respectively, both validated experimentally. A further increase in critical conditions was shown to be possible, using the proposed control mechanism.

Kitsios, Ooi and **Soria** discussed *"Anisotropic closure for the triple decomposition stability analysis of a turbulent channel"* as a prelude to global instability analysis of turbulent flows. Using the well-known work of the group of Reynolds in the early 1970s as their starting point, these authors developed and discussed a nonlinear closure model for the eigenvalue problem analysis of turbulent channel flow. In parallel, they conducted experimental work and compared theoretical and experimental results at a single frequency of 100Hz. As a general statement they found eddy-viscosity models to stabilize the channel eigenmodes. Direct and adjoint eigenmodes were determined from the Bi-Orthogonal decomposition technique introduced by Tumin (1996). The found that the reconstruction of (invariant in time) measured turbulent profiles using flow eigenmodes was most accurate when the nonlinear closure model was employed; subsequently, the same model coefficients were used in order to determine evolution of the profiles. These authors are presently active in extending the presented work to BiGlobal instability of complex turbulent flows.
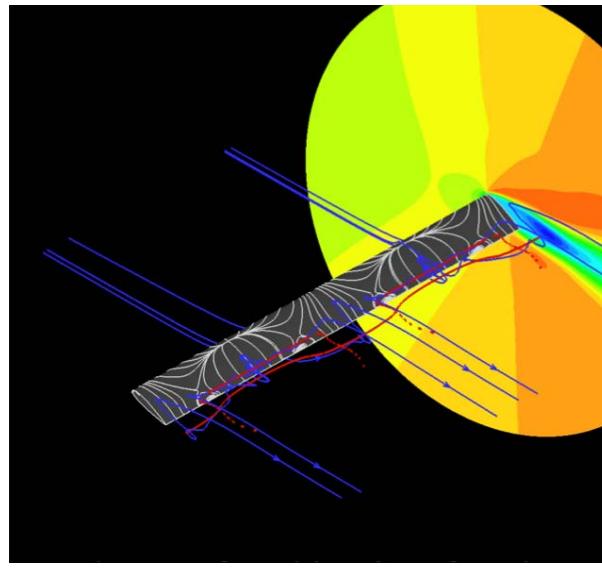

Figure 3. An image of stall-cells forming on a massively separated NACA0015 airfoil (Rodríguez and Theofilis 2010)

Rodríguez and Theofilis presented work on *"The origin of stall cells in airfoils"*. The departure point was analogous topological analysis by the same authors on separated flow on a flat-plate boundary layer, which revealed the origin of the phenomenon of "U-separation" to be in the linear amplification of the pertinent self-excited global mode. Applying the same topological analysis to the composite field constructed by the steady laminar flow in the wake of a massively separated NACA 0015 airfoil and its linearly superposed leading global eigenmode, these authors demonstrated the progressive three-dimensionalization of the nominally steady laminar 2-d flow, up to the formation of the characteristic stall-cell structures on the surface of the airfoil; a stall-cell image is shown in Figure 3. Favorable topological comparison of the proposed theoretical scenario with a plethora of experimental results was demonstrated.

Tsiloufas, Gioria, **Meneghini** and Carmo presented a **"Floquet stability analysis of flow around a stalled airfoil",** starting from a discussion of known global instability analysis results in the wakes of circular cylinders (Barkley, Henderson 1996; Blackburn, Marques, Lopez 2005), low-pressure turbine blades (Abdessemed, Sherwin, Theofilis 2009) and NACA0015 airfoils (Kitsios, Rodriguez, Theofilis, Ooi, Soria 2009; Rodriguez, Theofilis 2010) and Carmo, Shewrin, Meneghini (2010). While analogies were expected, strong differences have been documented at AoA=20deg, where flow is massively separated over the airfoil. The principal result is that the role of the short- and long-wavelength modes is reversed between the circular cylinder and the airfoil: in the latter application, the shorter-wavelength mode becomes unstable first at Re=450, while the long-wavelength mode becomes unstable at Re=600. Parametric studies are currently performed, while extension of the employed methodology to aeroacoustics research is envisaged in the near future.

2.3 Session III: Boundary and Shear Layers (Day 2)
(Session chaired by D. S. Henningson. Notes by V. Theofilis)

Peter Schmid presented an invited talk on *"Global modes, dynamic modes, microlocal modes",* and introduced iterative methods for the numerical solution of the ensuing large eigenvalue problems, paying particular attention to the Arnoldi algorithm. In the numerical part of the talk, the author introduced a Jacobian-free framework for the computation of global modes, as well as the Cayley spectral transformation as a means of rotating the basin of convergence of the Arnoldi algorithm. Instead of doing the inversion of the large discretized matrix in a direct manner, the author proposed using a BiCGSTAB approach, the slow convergence of which is accelerated by an ILU preconditioner. Regarding the different types of modes exposed, from a numerical point of view the calculation of the Dynamic Modes follows closely that of the Eigenmodes, the decisive advantage of the former over the latter set being analysis and reconstruction of nonlinear data. As a demonstrator, the author discussed instability of compressible flow over a swept attachment-line. A moving grid was used in order for the shock to adjust itself to perturbations and three mode branches were exposed in detail, that related with the attachment-line and crossflow instabilities, the branch of the acoustic modes and the branch originating at shock interactions. Dynamic Modes were then discussed as a means of decomposition of numerical data into coherent structures. The technique was validated using snapshots of plane channel flow at Re=10000, before being applied to study of Glauser's wake experiment, in which the experimental data were collected into a "snapshot basis", analogous to that formed by the Arnoldi process during the calculation of eigenvectors. Finally, Juniper's Schlieren movie of data (subsequently shown during Juniper's presentation) was reconstructed using a 5-mode Dynamical Mode reconstruction. The final part of the presentation was devoted to "Micro-local" modes, a term used to describe localized wavepacket modes in the framework of an analysis which shares the two-scale characteristic of weakly-nonparallel theories. In a boundary-layer context, the theory uses Fourier transforms

for the streamwise spatial direction without resorting to the parallel flow assumption and constructs modes which are expected to assist generalized receptivity studies.

Marquet and Sipp introduced *"Global forcing/forced modes in spatially developing flows: the flat-plate boundary layer"*, in a context of the differentiation between Oscillators and Amplifiers: the former are perceived as unstable temporal global (BiGlobal) modes, while the latter may be reconstructed by superposition of stable temporal global modes, as introduced by Akervik et al. (Eur J Mech / B Fluids); the authors presented an alternative means of calculation of amplifiers, based on forcing/forced perturbations, which circumvents the need for summation. The accuracy by which the eigenspectrum need be calculated in order for the reconstruction of Amplifiers to be reliable has been one of the major points of debate in the subsequent discussion: while all experts agreed that the correct boundary conditions for the inflow/outflow partial-derivative eigenvalue problem governing global instability of boundary-layer flow are unknown, and indeed the dependence of the spectra on numerical discretization details has been conclusively demonstrated in a global analysis context, some researchers feel that the particular details of the spectrum do not matter; their sum is purported to be robust – more details on this point are presented in the pertinent discussion session.
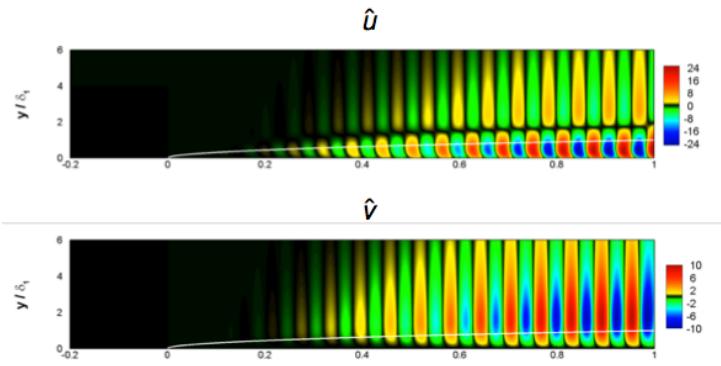

Figure 4. Tollmien-Schlichting instability recovered as a forced mode (Marquet and Sipp 2009)

In the presentation of Ehrenstein, **Passaggia** and Gallaire, entitled "*Control of a separated boundary layer: Model reduction using global modes revisited*" the (bump) geometry-generated laminar separation bubble instability was analyzed and controlled by means of a low-dimensional compensator, as introduced by Kim and Bewley (2007). The issue of mode selection for the construction of the (low-dimensional) mode controller was addressed and the effect of increasing the number of modes involved in the compensator coupling to the plant and integrating in time was addressed; it was shown that the energy carried by the streamwise perturbation can be reduced by several decades over long periods of time by consideration of an ever increasing number of modes in the bi-orthogonal projection. The main conclusion of this work has been that the bi-orthogonal projection is suitable for control of weakly unstable flows, while the proposed low-dimensional compensator could stabilize the bump-induced separated flow.

The work of **Medeiros**, Silva and Germanos *"Towards natural transition in compressible flow"* was motivated both by aerodynamic and by aeroacoustic considerations, drag reduction being commensurate with reduction in noise emissions. Given that natural transition, a precursor to turbulent flow in boundary layers, involves turbulent spots, prior to which wavepackets appear, the core of the work was devoted to enhancing understanding of the latter phenomenon, namely wavepackets in compressible flow. Perceived challenges addressed in the work by means of Direct Numerical Simulation have been the lack of localization of a wavepacket in neither spectral nor physical space, the changes that the dominant modes experience with changing Reynolds number and the broadband nature of the experimental spectra,

corresponding to measurement noise, as well as the fact that wavepackets support both fundamental and subharmonic resonances. Results shown included individual and combined wavepacket interactions of a 2-d packet in the middle of the neutral loop and a 3-d such perturbation near Branch I. These interactions were found to be an essentially linear mechanism and were presented as the missing link between interacting wavepackets and streaks in natural transition.
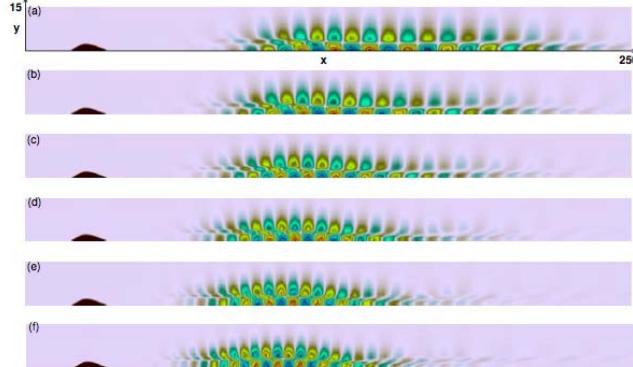

Figure 5. Leading global eigenmodes behind a bump on a flat plate, as a function of the protuberance height (Passagia, Ehrenstein and Gallaire 2009)

Cohen, Karp and Shukhman discussed *"The Formation of Packets of Hairpins in Shear Flows"*. Their contribution presented the development of a novel analytical-based solution method for the interaction between a general family of unbounded planar homogeneous shear flows and any localized disturbance. The solution is carried out using Lagrangian variables in Fourier space, an approach that is convenient in that it enables fast computations. In the present work the new method was utilized in an attempt to understand the generation of packets of hairpin vortices from a pair of counter rotating streamwise vortices embedded in uniform shear flow. Consistently with earlier work by the same group, the main present finding has been the observation, using experimental, numerical and theoretical results, that the formation and characteristics associated with the structure of a single hairpin, evolved from a dipole vortex, are very similar to the structures of those composing packets of hairpins in turbulent and transitional shear flows.

Higuera, Sánchez and **Vega** presented analysis on the *"Structure of streaks in a Falkner-Skan boundary layer"*, building upon earlier theoretical work by the same group on the Blasius boundary layer. The nature of streaks in the boundary layer was discussed, with particular emphasis on the near self-similar nature of optimal streaks, as known from the literature (Luchini 2000). It was shown that streaks in both the zero- and the adverse-pressure gradient flows, which are known to be optimal perturbations of the respective flows, and as such may be recovered by short-time solutions of the initial-value problem, may also be obtained as unstable modal perturbations, after appropriate scaling of the free-stream and boundary conditions. In the process, the free-stream behavior of the streaky perturbations has been obtained in closed form.

Tempelmann, **Hanifi** and Henningson, in their contribution *"Spatial Optimal Disturbances of Three-Dimensional Boundary Layers"*, introduced a new PSE method capable of capturing transient growth. The proposed method provides a new remedy for the ambiguity in the exponent and amplitude function, which classical PSE resolves by the auxiliary condition. Here, waviness is attached to the wavenumber or phase function alone, while growth is captured by the amplitude function, much like is done in the global modes analyses discussed elsewhere in the meeting. The new PSE also requires iteration, which starts at the external streamline. Validation of the novel approach has been provided by modal perturbations, while the adjoint

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equation and power iteration has been employed to capture optimal disturbances of Falkner-Skan-Cooke boundary layers. Both the Orr mechanism (initial vortices tilted against the mean flow shear) and crossflow modes have been recovered by the new approach. A unified N-factor calculation based on the new PSE method delivers different results from those based on the pure modal approach.

The invited talk by **Anatoli Tumin** on *"The Global (BiGlobal) Modes' Studies"* has been an attempt to distill the problem of computation of global modes to the simplest possible "box formulation", i.e. a tall rectangular computational domain, the short base of which is a piece of the flat-plate boundary layer, while its long base is a wall-normal distance several times the extent of the boundary layer itself; in the limit of uniform flow, such a flow configuration affords analytical solutions for various types of inflow/outflow and far-field boundary conditions and, as such, it lends itself as a benchmark configuration for global flow instability analyses (and codes). At the same time, the deliberately provocative character of this contribution has been one of the defining moments of the spirit of the Crete-IV symposium and was most appreciated by participants for its thought-provoking statements and the openness with which it treated current issues.

2.4 Session IV: Complex Flow Applications (Day 2)
(Session chaired by J. D. Crouch. Notes by V. Theofilis)

In his invited presentation **Hugh Blackburn** introduced *"Global stability and transient growth of physiological-type flows"*, discussing in detail computational approaches for instability analysis of complex flows, both in the short- and the long-time limit. Special attention was paid to the less explored transient growth phenomenon in arbitrary geometry flows. The operators involved in the direct and adjoint eigensystem analysis, and their relation to transient growth was elucidated, and the distinction between the state transition operator and its discrete analog was made. A time-stepping approach was proposed as an efficient technique for the calculation of both modal and non-modal instability. A two-loop approach, in which the outer loop computes the eigensystem and the inner loop applies the joint operator (ie the symmetric operator formed by applying the adjoint to the direct state transition operator), was employed in order to compute the eigensystem. As known from classic transient growth studies of one-dimensional base flows, it was shown that the Singular Value Decomposition of the state transition operator provides a convenient means of transient growth computation of complex flows too. The implementation of these ideas into an open-source spectral-element code was discussed and validations in parallel pulsatile pipe flow were shown. The physiological flow analyzed with respect to their linear modal and non-modal stability was a stenotic flow modeling the carotid artery in the limit of steady and pulsatile incoming flow. At Reynolds numbers of $O(100)$ values of energy gain in excess of $O(10^{23})$ were found, leading to growth of velocity perturbations of $O(10^{12})$ in finite time. The development of a modal perturbation of steady flow in a stenotic geometry is shown in Figure 6.

Figure 6. Jet/shear-layer modal instability of stenotic flow (Blackburn, Sherwin and Barkley 2009)

Monkewitz and Grandjean discussed *"Experimental investigation of 2D global modes in mixed Rayleigh–Benard–Poiseuille convection"*, using water and mineral oil at different Prandtl numbers as the working fluids. The geometry considered was a plane channel with large transverse aspect ratio, while the technique employed was impulse response of the system as a function of the Reynolds and Rayleigh number. It was verified that the onset of thermal convection comes in the form of transverse rolls and corresponds to the

transition from convective to absolute flow instability. The experimentation was then geared toward comparisons with earlier theoretical and numerical work by the same authors, and the observed instabilities could be classified as being analogous with the "steep" nonlinear one-dimensional modes of previous theoretical investigations.

Kuhlmann and Schoisswohl presented work on *"Thermocapillary flow instabilities in open cylindrical pools"*, applications arising in electron beam evaporation, welding, diverging solutocapillary flow in dishes and, not least, space experiments. Out of several possibilities, a Reynolds number was defined and the pertinent eigenvalue problem was formulated, while the basic flow whose instability it investigates is akin to the union of those in lid-driven cavities. Convergence history was presented and several instability mechanisms were discovered, of which only those pertinent to Pr=0 were presented. Cuts through the cylindrical domain, near the top-/mid-plane and in-between were shown to resemble centrifugal-wave instability. In a shallow pool, the dominant instability takes the form of a hot-spot in the center, surrounded by a cold rim; the corresponding eigenvector peaks at the location of maximum radial gradient of the axial flow, while the underlying physical mechanism is surprising analogous only to detonation instabilities.

The presentation of **Gudmundsson** and Colonius on *"The effects of nozzle serrations on the linear stability characteristics of turbulent jets"* started by showing experimental evidence, collected from several nozzles of distinct serration patterns, on the dependence of Sound Pressure Level on Strouhal number. From a theoretical point of view, the linearized Navier-Stokes equations were written as a 2-d eigenvalue problem, solved by ARPACK. The EVP was then reduced into a single PDE, the two-dimensional Rayleigh equation for the pressure perturbation first discussed by Hall and Horseman (1990), which is valid for both temporal and spatial analysis and may be solved by multidimensional shooting. The mean flow analyzed was obtained from Stereo-PIV. Pressure perturbation results, compared with experimental results obtained on the 78-mic-on13-rigs platform at NASA Glenn, showed that the serrated jets, although initially more unstable, later they decay faster than their non-serrated counterparts. Finally, a PSE-type quasi-parallel approach was employed and the amplitude of instability waves was determined via a least-squares approach, which resulted in reasonable shape predictions over a limited axial range at different Strouhal numbers.
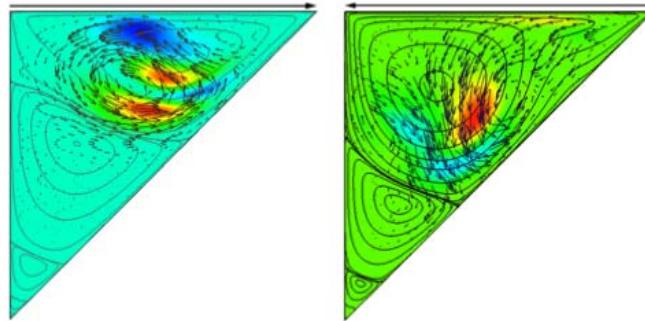
Figure 7. Global eigenmodes of triangular lid-driven cavities (Ahmed and Kuhlmann 2009; González and Theofilis 2009)

Romm and **Greenblatt** discussed experimental work on *"Swirl-Induced Transition Control in Subcritical Pipe Flows"*, motivated by the need to sustain turbulent flow in pipes below the theoretical limit of Re=2300. Local swirl, induced by dielectric (DBD) plasma actuators, was selected as active flow control means, exploiting instabilities of subcritical pipe flow. The experimental setup, consisting of axisymmetric and swirl actuators, was presented in detail, and the governing parameters of the problem (Reynolds number, duty cycle,…) were identified. A configuration down-selection was performed and it was found that the

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Helmholtz resonator performed satisfactorily as a flow control device. In the subsequent optimization performed, the swirl-actuator was found to be substantially superior to its axisymmetric counterpart. It was speculated that vortex breakdown was responsible for the better performance of the swirl actuator.

The contribution of Ahmed and **Kuhlmann** entitled *"Instability of Lid-Driven Triangular Cavity Flow"* discussed theoretical and experimental linear instability analyses of lid-driven cavity flows, the cross-section of which is of isosceles triangular shape. Two distinct flow configurations were considered, one in which lid motion is away from and one towards the right-angle. The respective critical conditions were identified numerically by a finite-volume approach, and compare favorably both with experimental work performed by the same group and by independent finite-element global instability analyses by González and Theofilis (unpublished). Images of the respective leading eigenmodes are shown in Figure 7.

Swaminathan and Govindarajan presented *"Global instabilities in non-symmetric convergent-divergent channels"*. After introduction of the geometrical definition of the problem, the single equation on which the two-dimensional global instability analysis is based was exposed, alongside the numerical techniques for its solution. Notably, this contribution was the only one in which the full eigenspectrum calculation was performed, using the QZ algorithm, fine grids, and weeks of computing time per wavenumber. The asymmetric geometry was defined in terms of the waviness height and the minimum half-width, without assuming periodicity along the axial spatial direction; as validation, periodic eigenfunctions were recovered in the symmetric geometry case. At low Reynolds number the reverse-asymmetric geometry was found to be more unstable than its forward-asymmetric counterpart. The leading eigenmode of the former case is shown in Figure 8. The modal transition scenario is proposed as potentially underlying an efficient mixing-enhancement methodology at subcritical Reynolds numbers. When the Reynolds number increases many near-neutral modes appear, strengthening the speculation that transient growth may be an alternative path to transition in this geometry.
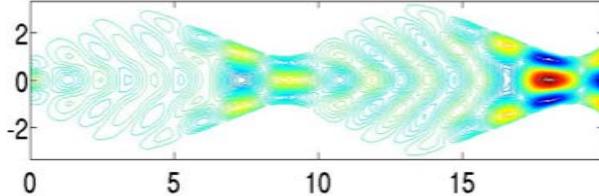
Figure 8. Leading eigenmode of the reverse-asymmetric converging-diverging channel geometry at Re=10 (Swaminathan and Govindarajan 2009)

The contribution of **Juniper** on *"Non-normal triggering in thermoacoustics"* discussed thermoacoustic instabilities as demonstrated in the Rijke tube. Feeble transient growth was found by analyzing a simple model of the compressible equations and "bypass transition analogues" were examined: using an n-mode Galerkin expansion, it was possible to move between stable and unstable periodic solutions. Three results of significance were reported: First, the nonlinear system locks in the stable periodic solution. Second, a procedure for the calculation of optimal initial conditions for the nonlinear governing equations was put forward, based on identifying the local optimal initial state by adjoint looping of the nonlinear or linear governing equations, nested within a conjugate gradient algorithm. Third, most importantly, safe operating conditions for the Rijke tube were calculated. The main conclusion has been that nonlinear analysis of thermoacoustic systems is mandatory, since analysis indicates linear stability.

2.5 Session V: Theoretical Flow Control (Day 3)
(Session chaired by P. Luchini. Notes by V. Theofilis)

Rowley, Mezic, Bagheri, Schlatter and **Henningson** exposed *"Spectral analysis of nonlinear flows"*, by first introducing the concepts of Koopman operator and related modes. The Koopman operator is an infinite-dimensional linear operator, associated with the full nonlinear system, and propagates a scalar function forward to its value at the next snapshot. Using the Koopman system, any state may be expanded into eigenfunctions, the expansion coefficients of which are vectors; the expanded state may be taken directly from observation, either numerical or experimental. For a linear system the Koopman modes are exactly its global modes. For a periodic nonlinear system, the Koopman system is exactly the discrete Fourier transform. From a practical point of view, Ruhe's implementation of the Arnoldi algorithm produces the Koopman modes. Snapshots may be expanded and the amplitude of the calculated Koopman modes may be utilized in order to distinguish between valid and spurious such modes produced in the calculation. The newly introduced system was compared with expansions based on global flow eigenmodes and the Proper Orthogonal Decomposition. A three-dimensional jet-in-crossflow was used in order to demonstrate that the Koopman modes are capable of capturing the dominant frequencies and recovering the spatial structure of the leading perturbations.
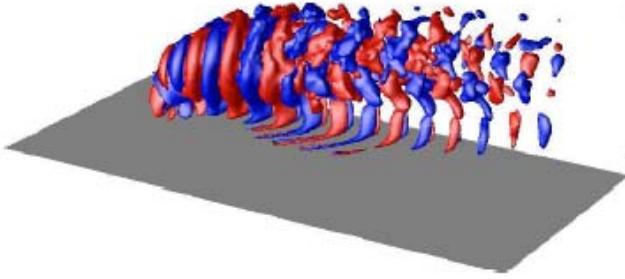

Figure 9. Streamwise velocity perturbation in a jet-in-crossflow application, captured as a Koopman mode; colors denote positive and negative perturbation levels (Rowley, Mezic, Bagheri, Schlatter and Henningson 2009)

Barbagallo, Sipp and Schmid introduced *"Closed-loop control of cavity flow using reduced order models"*. After performing an eigenvalue problem solution of incompressible flow in a model open cavity using $O(10^6)$ coupled degrees of freedom, model reduction is performed, which delivers $O(10^1)$ dynamically relevant modes. Modally unstable conditions are chosen in order to perform flow control and a Linear Quadratic Gaussian control strategy, based on the reduced order model constructed is followed. Models explored for the unstable subspace have been the global flow eigenmodes themselves, while in the stable subspace both the global modes and balanced POD modes, introduced by Rowley (2005), were used. The key conclusions drawn are that the global modes produce unsuitable bases for flow control and that the balanced POD modes not only are suited for this task, but also are capable of controlling the flow with a relatively small number of BPOD modes.

The presentation of **Illingworth**, Morgans and Rowley on *"System identification and robust feedback control of two-dimensional cavity oscillations"* dealt with the representation of open cavity oscillations in compressible flow by a linear transfer function, and the required system identification procedure prior to building a reduced order model. System identification is achieved by a combination of body-force introduced at the upstream end of the cavity, in the vicinity of the shear-layer, and pressure measurements at the downstream cavity corner. Spectral analysis is utilized in order to identify the open-loop transfer function. The Eigensystem

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Realization Algorithm of Juang and Phan (2001) was used in order to construct a reduced-order state-space model and a LQG robust control was subsequently employed in order to stabilize the flow. Performance was validated individually on acoustics and scattering, such that the overall linear model consisted of a superposition of the individually validated elements. The functionality of the controller was found to be Mach-number dependent: at Mach numbers 0.4 and 0.5 closed-loop stability is achieved, while oscillation amplitudes are still reduced by the controller at 0.7 and 0.8.

Minutes of Discussion Groups

1. **On Streamwise Vortices**
   (Introduced by I. Wygnanski. Presentation summary by V. Theofilis. Discussion notes by D. Greenblatt)

Wygnanski's invited talk on Streamwise Vortices presented experimental facts and interpretation of results in a wide variety of applications, before raising a series of questions, cited below. Some of the points made follow. Spanwise 2-d vorticity is what one manipulates, when one does separation control. Bending instability of large spanwise vortices leads to "bulging" instability, just by having a serrated nozzle (like chevron nozzle). This led to the V-shaped nozzle. In the centerline measurements lead to classic mixing layer. By doing a moving-origin, also mixing layer results are measured. The question is why does the mixing layer at the centerline moves upward? The answer is that the flow behaves like a wake. One application is the "lambda wing". Dimples delay separation in Low Pressure Turbines. Missile-like shape at an angle of incidence (or refueling tube). What happens is that when the cylinder is forced there is a definite effect of spanwise flow. Vorticity is shed in a staggered way. Far downstream, after uniform forcing in one side only, redistribution of vorticity in uniformly distributed cells occurs. In the absence of this forcing, symmetric flow pattern re-establishes itself. In the V22 application, fairly large vortex generators exist and reduce a lot of drag, the vortices surviving to the trailing edge (in turbulent flow). In a Turret, the BL height is high enough to generate necklace vortices, which affect separation. In a Turbulent Spot in a laminar BL generated by pulsing the jet, necklace vortices wrap around the jet (Fric & Roshko 1994: jet-in-crossflow).

Questions raised by Wygy:

- How to control these vortices
- How to make them more stationary (and thus more observable)
- What it the role of delay of separation or in transition
- What is their effect on heat transfer
- How do they affect (enhance or limit) the application of active flow control

A round-table discussion followed, the key interactions of which are summarized below:

Wygy: How do we control streamwise vortices and how do they interact with various geometries. Question: Can we make generalizations, e.g. are they unique and are their characteristics the same?

Kim: What is important is the mean shear time scale to the turbulence time scale. If you have a shear flow, you generate the streamwise vortices.

Wygy: But why is normal (vertical) vorticity converted to streamwise vorticity, what is the rate of this process; is there amplification?

Kim: It depends how long the vortex is exposed to the shear.

Monkewitz: The wall plays a dominant role: for example spanwise vortices can be represented by dipoles while streamwise vortices are represented by dipoles and are therefore different.

Wygy: One suggestion is to increase velocity ratio (in a shear layer) in order to increase shear and then measure spatially how quick they turn and become streamwise vortices.

Kim: Timescale for turbulence is important. It must be large [to sustain the vortices?]

Unknown: Only streamwise vortices will survive in the shear. Transverse vorticity is destroyed by the shear.

Wygy: But it is not the case for the 2D mixing layer.

Fasel: The 3D disturbances must grow.

Kim: We observed that 2D simulation is very close in the mixing layer but very different in boundary layer flows.

Fasel: The mixing layer supports a secondary instability

Tumin: We must distinguish between 2D and 3D mixing layers. A 3D stationary mode is like a cross-flow instability.

Wygy then raised the question of how do we *actively control* these vortices?

Greenblatt: Based on your comments earlier, it seems that passive 3D perturbations (VGs, dimples, chevrons) are very effective and do not bode well for 2D active control.

Wygy: One way to control streamwise vortices is to use sweeping jets act which act in some ways like VGs. He pointed out that they spread more because they oscillate, but they entrain less fluid. This was shown by Robert Bridendal? who showed that there is an order of magnitude less entrainment in oscillating jets. They are apparently more effective zero mass-flux jets.

Monkewitz: But oscillating jets entrain a lot?

Wygy: Plans to do measurements on larger oscillating jets. They require less mass flow.

Greenblatt: These still remains the plumbing problem air has to reach these actuator in contrast to "autonomous" driven electrically.

Fasel: Sweeping fluidic actuators ones cover more wing area. How can we determine the correct time scale or spacing of these actuators? The frequency of the sweep is important.

Wygy: If we increase the pressure, we increase the freq as well as mass and mom as well.

Fasel: Could we tune the actuators so that sweep freq could be related to boundary layer instability.

Wygy thinks that the nozzles are chocked, i.e. sonic flow in the nozzles.

Fasel: Sailplane designs are so advanced that they used spanwise and chordwise roughness to control the flow passively.

Wygy: Did anyone use plasma locally? Deploying the plasma in a three-dimensional sense, may be a way to get around the low momentum of the plasma. A major objective is to generate larger circulation or vorticity.

Monkewitz: What about the problem of getting rid of streamwise vortices. E.g. on the coanda cylinder.

Wygy: Yes we like to achieve this on the Coanda because for forced wall jet separates early forcing decelerates the jet faster.

Fasel: Can transient growth tell the optimum scaling?

Tumin/Unknown: No, it needs a time scale. Real transient growth does not mean optimum transient growth.

2. The Global (BiGlobal) Modes' Studies
   (Introduced by A. Tumin. Presentation summary by V. Theofilis)

Tumin first exposed a list of questions, attached in what follows, and opened the floor for presentations and questions. Rodriguez talked of the difficulties encountered in converging vorticity modes by a 2-d eigenvalue problem approach. He asserted that in the case of the Orr-Sommerfeld limit a large number of nodes is necessary in both the x and the y spatial directions. A discussion, summarized below, followed.

Sherwin: One can never have the dispersion relation converged. At best, one can get convergence with a sub-part of the spectrum. Blackburn and Schmid agree: "one will never get the straigh lines".

Schmid: Use analytic boundary condition.

Marquet: It is important to look at the distinction between oscillator and amplifier. What about superposition?

Schmid: For transient analysis, it is not important to obtain the eigenvalue correctly, what is important is the correct relation between modes.

Chomaz: Agrees with Schmid and states that what is robust is the pseudospectrum. It's hopeless to aim at correct capturing of the spectrum, one should aim at recovering the pseudospectrum. This behavior is demonstrated in the advection-diffusion equation.

Tumin: Someone should take uniform flow and explore the pseudospectrum. Otherwise it sounds plausible, but it's not proven.

Henningson: the resolvent from an unresolved spectrum (Butler's thesis) came out very robust. The exact value of the eigenvalue did not.

Chomaz/Schmid: Use Ginzburg-Landau for pseudospectrum exercise as a benchmark.

Luchini: Presented "a short history of time" (well, just 50 years ago) and asked himself, why would one want to use all the extra computational cost for a problem that can be solved by simpler means?

Crouch: The oscillator is not an issue, it's the amplifier one cares about. He's not satisfied by any of the Blasius solutions he has seen. He wants to see zero amplification in time, and right frequency. A correct solution should permit putting a probe and measuring (correctly) growth from Branch I to Branch II. Modes seen so far, do not satisfy this criterion. In terms of modal behavior he tried to get closer to zero growth rate. Can it be done? Statement: that's fine to say one should use combination, but he's not satisfied.

Henningson: What is the problem with global modes? In his view, "we have something". Modes should be damped, indicating that boundary-layer flow is convectively unstable.

Tumin: why should the damping be box/dependent? Shape functions are identical as those coming from spatial OSE under any/all of Dirichlet, Neumann or Robin BC, but spectra are very different.

Kim: What is a global mode good for? One never uses the eigenfunctions of OSE as basis for an expansion! The present situation reminds him of the early days of POD. Great looking eigenfunctions, are they useful?

Sherwin: If the issue is numerics, one should not use the wrong method. Wake flows are perfect examples of modal amplification.

Fasel: One should distinguish between the amplifier and oscillator problems. Any time a new tool has been developed, one has to have a purpose. What is the purpose of using massive global modes? The base flow takes massive amount of time anyway.

Sherwin: One purpose is to identify easily where to put control

Marquet: One should not look at the temporal global modes for amplifier flow, one should simply compute the left and right singular vectors. If the application is indeed an amplifier, one direct and one adjoint eigenspectrum computation delivers all the necessary information.

3. The Global Modes Studies:
Status Quo, Existing Concerns and Proposed Actions

Text based on a Discussion Session between the following contributors:
Chomaz, Crouch, Gonzalez, Henningson, Kim, Luchini, Rodríguez, Schmid, Sherwin, Theofilis, Tumin

The Status Quo:

1. The global (bi-global) modes studies have demonstrated a significant progress in development of computational methods

2. The global (bi-global) modes tool is very promising for application in a various areas of fluid mechanics

3. Some global modes have proven physically insightful, i.e. bluff body flows

4. Some observations on the calculation of global modes in Blasius flow:
   a. The solution of a PDE is completely determined by BC, thus there is no surprise that the spectrum depends on the BC and domain
   b. The expansion of a localized disturbance in global modes can be used to understand the movement of the global OS branch. The resulting TS wavepacket is convectively unstable and all modes must be damped, thus the spectrum must be displaced downward compared to the parallel flow case
   c. Numerical results indicate that away from the boundaries the envelope of global TS-mode are identical to local spatial growth, the shape functions of local and global modes are identical and the TS wavepacket development is the same
   d. Note also that the sum of modes may describe the same solution although the spectrum changes
   e. A global TS mode must be forced with i.e. a numerical vibrating ribbon to represent the physical development of a TS wave

Our Concerns:

1. The primary concerns are associated with convective instabilities, where none of the global modes yet calculated appears to be physical

2. In the historical record of stability research "amplifier" problems were solved first, using local theory and its variations. In local theory they are overtly easier than their "oscillator" siblings; one should expect the same to occur even when local theory does not apply

   Determining the amplification (frequency response) of an "amplifier" flow directly from its linearized Navier-Stokes discretization is indeed easier, and computationally less demanding, than determining it by calculating its discrete modes first. Why would one want to pay the extra computational cost?

3. Global modes, as originally introduced in a boundary-layer context, are self-excited oscillations that do not require external forcing to be maintained. In open flows they may occur in any number, or not at all. When there is an unstable mode, the flow can be classified as an "oscillator" (if unidirectionally uniform, as absolutely unstable); when the flow is globally stable but an external excitation gets spatially amplified, as an "amplifier" (if unidirectionally uniform, convectively unstable). The numerical representation of an open flow, in contrast to its continuous differential equation, exhibits discrete modes that typically form a complete basis but change with size and resolution of the computational box.

   Not all discrete modes (possibly none of them) approximate global modes; the distinction, especially for the benefit of the younger researchers, should be kept in the terminology that we use.

4. A heuristic interpretation of temporal modes as representing spatially growing perturbations does not have a mathematical background

5. Effects of the box size and spectrum resolution have not been explored properly yet, because of contemporary computing limits

6. How can BCs at infinity be included into the "box formulation"?

7. Ensure one understands the properties of the numerical schemes before determining the spectra of the discrete operator

8. How does one determine the receptivity of the initial conditions to the physical disturbances?

9. The global eigenmode expansion is one of many possibilities in representing flow dynamics, and in many situations it is not the preferred expansion (eg, we rarely use the eigenmode expansion for local problems). So, it is imperative to understand what the global eigenmodes are good for and for what flow problems they are preferred modes, rather than applying them blindly.

10. Rather than exploring use of the new tools for solving old (and solvable by less fancy means) problems, application of the new tools to acquire knowledge in areas where only these tools can help is encouraged. Candidate applications are: compressible flows on simple geometries (eg SBLI, MHD, detonation…), complex flows (corners, variable-area intakes, …)

What Should be Done?

1. Choose benchmarks for evaluation of the box size and resolution effects

2. Using global normal modes for projection of perturbations has to be accompanied by studies of various sets of eigenfunctions

3. General conclusions about efficiency of global normal modes for model reduction without exploration of various perturbation fields should be avoided

4. Imposing boundary conditions is a necessity for numerically representing flow in an infinite domain. Much effort has been spent over the years to design proper outflow boundary conditions (advective, characteristic, extrapolatory boundary conditions, one-way wave equations, perfectly matched layers, etc.). A global mode analysis in an open flow depends on the boundary conditions imposed on the "box modes", and the global modes in the box will represent the "infinite box" global modes to the extent of the boundary condition for the "box modes" approximating the true boundary condition. For example, the computed continuous spectrum for a boundary layer (in a local or global analysis) will never be able to approximate the analytical expression for the continuous spectrum.

For amplifier-type flows the exact location of the eigenvalues is often irrelevant, since only an eigenvector expansion based on multiple modes represents the underlying disturbance dynamics. While the perturbation dynamics is a robust feature of the flow, the spectral representation in terms of exponentially growing/decaying structures is not.

The choice of structures to represent certain aspects of the flow (global modes, adjoint global modes, frequency response, POD modes, balanced modes, etc.) cannot be separated from an application goal (stability analysis, receptivity study, shape optimization, control design). **A representation that works for one application may be entirely inappropriate for another.**

To study some of the above issues, it is suggested to work through an example based on the Ginzburg-Landau equation with complex coefficients. This equation models the generic fluid-dynamic processes of advection, diffusion, dispersion, convective, absolute and transient growth. Exact solutions for the global modes in an infinite domain are known for this equation and can be used to determine the influence of a truncated domain, of numerical discretization schemes and of imposed boundary conditions on the global spectrum.

5. The global modes need to be shown to give the right spatial growth characteristics and no temporal growth at a fixed point spatially – this would imply a zero growth rate.

If the global modes do not exhibit this character, they are not physical modes (e.g. the are not TS waves), but are rather numerical modes specific to the numerical formulation of the problem. They may be useful as a numerical basis, but they are not physical modes.

The physical problem of convective instability requires a forcing. If the forcing is associated with the excitation of an eigenmode (receptivity), that mode must be physical. If the forcing produces a forced response (non-modal), then the eigenmodes appear unimportant to the physical problem.

Global Flow Instability and Control IV
Sept 29 - Oct 2, 2009

Final Schedule In Detail

Mon, Sept 28 pm

17:00-19:00	Registration	
19:00-21:00	Welcome Reception	

Tue, Sept 29 am

08:00-08:45	Registration	
08:45-09:00	Opening Comments	

Session I: Theoretical Foundations (Chair: Schmid)

09:00-09:45	**Kim**	**Physics and control of turbulent boundary layers**
09:45-10:05	**Hall**, Sherwin	Streamwise vortices in shear flows - Part A: Analysis of a vortex-wave interaction
10:05-10:25	**Sherwin,** Hall	Streamwise vortices in shear flows - Part B: Numerical modelling of a vortex-wave interaction
10:25-10:45	Discussion	

Coffee/ Tea Break

11:15-11:35	Okino, **Nagata**	Nonlinear solution of flow in a square duct
11:35-11:55	Meliga, **Chomaz**	Global stability and adjoint-based control of a confined impinging jet
11:55-12:15	Garbaruk, Magidov, **Crouch**	Quasi-3D analysis of global instabilities: vortex shedding on a wavy cylinder
12:15-12:35	**Luchin**i, Giannetti, Pralits	Sparse-matrix algorithms for global eigenvalue problems
12:35-12:55	Discussion	

Lunch Break

Tue, Sept 29 pm

Session II: Lifting surfaces - analysis and experimentation (Chair: Monkewitz)

14:30-15:15	**Fasel**	Reynolds number effects of separation control for lifting surfaces: simulations, laboratory and free-flight experiments
15:15-15:35	Stalnov, Fono, **Seifert**	Closed-Loop Bluff-Body Wake Stabilization via Fluidic Excitation
15:35-15:55	**González**, Artana, Gronskis, D'Adamo	An electrodynamic analogy of the moving surface control mechanism in bluff bodies
15:55-16:15	Discussion	

Coffee / Tea Break

16:45-17:05	Kitsios, Ooi, **Soria**	Anisotropic closure for the triple decomposition stability analysis of a turbulent channel
17:05-17:25	**Rodriguez**, Theofilis	On the birth of stall cells on airfoils
17:25-17:45	Tsiloufas, Gioria, **Meneghini**, Carmo	Floquet stability analysis of flow around a stalled airfoil
17:45-18:05	Discussion	

Dinner Break

	Discussion Sessions:	
	I and II	
20:30-20:45	Wygnanski	On the generation and perseverence of streamwise vortices and their possible utilization in flow control
20:45-21:00	NN	TBA
	Discussion Groups	
21:00-22:30	Meet at	Open Bar

| 22:30 | | **Close Day 1** |

Wed, Sept 30 am

Session III: Boundary and Shear Layers (Chair: Henningson)

08:00-08:45	**Schmid**	**Global modes, dynamic modes, microlocal modes**
08:45-09:15	**Marquet**, Sipp	Global forcing/forced modes in spatially developing flows: the flat-plate boundary layer
09:15-09:35	**Cherubini**, Robinet, Bottaro, De Palma	The global optimal wave packet in a boundary layer and its non-linear evolution
09:35-10:05	Ehrenstein, **Passaggia**, Gallaire	Control of a separated boundary layer: Model reduction using global modes revisited
10:05-10:30	Discussion	

Coffee/ Tea Break

10:50-11:10	**Medeiros**, Silva, Germanos	Towards natural transition in compressible flow
11-10-11:30	**Cohen**, Karp, Shukhman	The Formation of Packets of Hairpins in Shear Flows
11:30-11:50	Higuera, Sanchez, **Vega**	Structure of streakes in a Falkner-Skan boundary layer
11:50-12:10	Tempelmann, **Hanifi**, Henningson	Spatial Optimal Disturbances of Three-Dimensional Boundary Layers
12:10-12:30	**Tumin**	**Towards the foundation of a global (bi-global) modes concept**
12:30-12:50	Discussion	

Lunch Break

Wed, Sept 30 pm

Session IV: Complex Flow Applications (Chair: Crouch)

14:00-14:45	**Blackburn**	**Global stability and transient growth of physiological-type flows**
14:45-15:05	**Monkewitz**, Grandjean	Experimental investigation of 2D global modes in mixed Rayleigh–Benard–Poiseuille convection
15:05-15:25	**Kuhlmann**, Schoisswohl	Thermocapillary flow instabilities in open cylindrical pools
15:25-15:45	**Gudmundsson**, Colonius	The effects of nozzle serrations on the linear stability characteristics of turbulent jets
15:45-16:05	Romm, **Greenblatt**	Swirl-Induced Transition Control in Subcritical Pipe Flows
16:05-16:25	Discussion	

Coffee / Tea Break

16:45-17:05	**Ahmed**, Kuhlmann	Instability of Lid-Driven Triangular Cavity Flow
17:05-17:25	**Swaminathan**, Govindarajan	Global instabilities in non-symmetric convergent-divergent channels
17:25-17:45	**Juniper**	Non-normal triggering in thermoacoustics
17:45-18:05	Discussion	

18:45 - 20:30 Symposium Dinner

	Discussion Sessions: III and IV	
20:30-20:45	Tumin	The global mode studies: what should be done?
20:45-21:00	NN	TBA
21:00-22:30	Discussion Groups Meet at	Open Bar
22:30		**Close Day 2**

Thu, Oct 1

Free Day	(Optional) Excursion to Santorini

Fri, Oct 2 am

Session V: Theoretical Flow Control (Chair: Luchini)

08:30-08:50	Rowley, Mezic, Bagheri, Schlatter, **Henningson**	Spectral analysis of nonlinear flows
08:50-09:10	**Barbagallo**, Sipp, Schmid	Closed-loop control of cavity flow using reduced order models
09:10-09:30	**Illingworth**, Morgans, Rowley	System identification and robust feedback control of two-dimensional cavity oscillations
09:30-09:50	**Ekaterinaris**	MHD flow control of shock-induced separation
09:50-10:10	Discussion	
		Coffee / Tea Break
10:30-11:30	Reports of the Discussion Groups	
11:30-12:30		**Symposium summary (Fasel)**

Close of Day 3 and Global Flow Instability and Control Symposium IV